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Exploring Vehicle Level Benefits of Revolutionary Technology Progress via Aircraft Design and Optimization

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Abstract: It is always a strong motivation for aeronautic researchers and engineers to reduce the aircraft emissions or even to achieve emission-free air transport. In this paper, the impacts of different game-changing technologies together on the reduction of aircraft fuel consumption and emissions are studied. In particular, a general tool has been developed for the technology assessment, integration and also for the overall aircraft multidisciplinary design optimization. The validity and robustness of the tool has been verified through comparative and sensitivity studies. The overall aircraft level technology assessment and optimization showed that promising fuel efficiency improvements are possible. Though, additional strategies are required to reach the aviation emission reduction goals for short and medium range configurations.

Keywords: aircraft conceptual design; fuel efficiency; multidisciplinary design optimization; laminar flow control; load alleviation; modeling and simulation; technology assessment

1. Introduction

Despite the dramatic progress in the past decades, aviation industry is still facing significant pressure in reducing fuel consumptions, emissions and costs, especially when it comes to the ambitious goals set by aviation authorities such as Flightpath 2050 [1] in Europe. To have a quantitative impression, the aviation emission reduction goals in the US and in Europe for both short term and long term are summarized in Table 1.

To realize the challenging goals aforementioned, researchers and engineers endeavor to develop new concepts and technologies. In 2013, IATA Technology Roadmap [2] has identified 24 potential airframe and propulsion technologies which might be available for sustainable aviation in 2050 time frame according to technology readiness level. Within the US NASA N-plus programs, a couple of innovative airframe technologies have been identified to reduce emissions [3,4]. However, both IATA and NASA studies have concluded that the technology development alone cannot reach the desired emission reduction goals; novel aircraft concepts needs to be developed to achieve the target aircraft performance. Graham et al. [5] from University of Cambridge have summarized different novel aircraft concepts proposed by aviation research communities and have concluded that ACARE and NASA emission goals cannot be achieved without developing transformational concepts. To support this claim, the historical development of commercial aircraft fuel efficiency since 1980 is shown in

Figure 1. Note that the selected aircraft are commercial airliners from regional aircraft to long-range wide-body aircraft. From this figure, one can observe the difficulty of realizing the emission goals, as the rate of reduction in fuel consumption is not high enough. To investigate the reason Figure 2 presents the so-called S-curve of the performance of civil transport aircraft from the aviation pioneering age till today, where payload range efficiency (PRE) is abbreviated from payload range efficiency (PRE = payload mass × range/fuel mass) [6]. It can be seen that a dramatic improvement in aircraft performance can be achieved only by introducing new technologies and/or new aircraft concepts.

Table 1. A summary of the CO_2 emission reduction goals (adapted based on Graham et al. [5]).

Aviation CO_2 Emission Reduction Goals			
Europe (relative to year 2000 a/c)		US (relative to year 2005 best-class a/c)	
Vision 2020	FlightPath 2050	N + 2 (2025)	N + 3 (2030–2035)
50%	75%	50%	60%
Air Transport Action Group (ATAG) targets 50% overall CO_2 emission reduction by 2050 relative to the baseline year 2005			

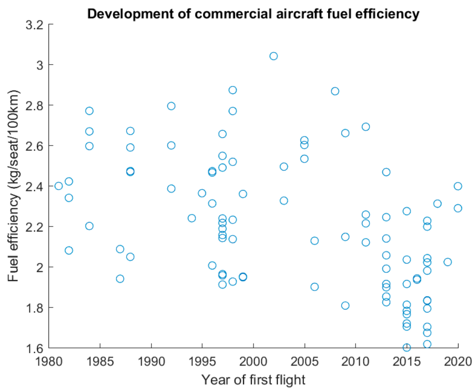


Figure 1. The historical development of commercial aircraft fuel efficiency (data mainly based on manufacturer brochures).

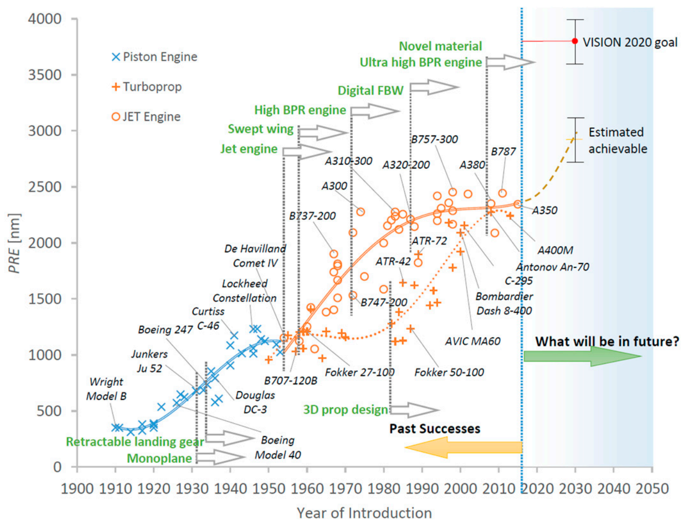


Figure 2. Development of the payload range efficiency (PRE) from the aviation pioneering age to 2050 [6].

Within this context, a joint research project "Energy System Transformation in Aviation, EWL (EWL is abbreviated from German words Energiewende in der Luftfahrt, which is an interdisciplinary project in Germany conducted by Technische Universität Braunschweig, Leibniz Universität Hannover, HBK-Braunschweig, DLR, PTB and Fraunhofer-Gesellschaft)" has been initiated in Germany to identify and further study possible transformative energy systems that can be used for civil transport aircraft in combination with target game-changing technologies. In this paper, potential technologies are firstly discussed from an aircraft design perspective. Then, the overall approach and also the component modelling methodologies are presented. After that, aircraft level results for integrating different technologies are also presented. To give a better overview of the presented results, further implications of the results are discussed at the end.

2. Overview of Game-Changing Technologies

Before illustrating the modelling approach, it is reasonable to take a look at the potential technologies that are investigated. As such, the game-changing aircraft-associated technologies identified within the project are briefly discussed and the methods for preliminary studies at the aircraft level are presented.

2.1. Laminar Flow Control

Laminar and turbulent boundary layers as well as the transition are of key importance with respect to aircraft friction drag and its impact on pressure drag because drag is significantly lower for laminar flow. Together with the cumulative effects on the overall aircraft design level the laminar flow technology is a key enabler for further reductions of fuel consumption.

The development of laminar airfoils and wings had begun already in the early phases of aviation and is today well applied for glider and small aircraft [7–11]. The application for transonic aircraft is still a challenge due to the transition of laminar to turbulent flow at the Reynolds- and Mach numbers of such aircraft. In addition, geometric surface imperfections can trigger transition too.

For short range aircraft with moderate cruise flight speeds and low wing sweep angles, laminar flow on the wing can be achieved by shaping the airfoil and wing contours and the associated pressure distributions accordingly. This is called Natural Laminar Flow (NLF). For long range aircraft, higher cruise Mach and Reynolds numbers are mandatory, and therefore a combination of contour shaping and active flow control (suction), the so-called Hybrid Laminar Flow Control (HLFC) is necessary to achieve laminar flow. Figure 3 shows how Reynolds number and wing sweep influence the applicability of NLF or HLFC technologies.

Over the last decades extensive NLF and HLFC research has been performed worldwide on various aspects, e.g., imperfections of contours, systems integration, and this has resulted in significant progress [12–16]. Several projects have been conducted for example, at DLR (German Aerospace Center), Airbus, and the Technical University of Braunschweig, including theoretical design work as well as flight experiments [17,18]. Currently large scale flight tests are ongoing in Europe [19,20]. In addition, the NLF and HLFC technologies have been assessed on conceptual and preliminary aircraft design level and have shown potential for mission fuel burn reductions of 5–10% for conventional and semi-conventional aircraft configurations [21,22]. Further research for more radical configurations is necessary, e.g., high aspect ratio wing configurations, low-noise aircraft, hybrid-wing-body.

Within the EWL project, more aggressive breakthrough on laminar flow control (LFC), i.e., full LFC, is aimed for more substantial aerodynamic drag reductions. Preliminary in-house study has shown that 90% of the total wing and tail plan surfaces can be laminarized, and 70% of the total fuselage surface can be larminarized. For the first stage system study, we define an LFC factor to reflect the percentage of the total aircraft surfaces that can keep in laminar flow status through laminar flow control technologies.

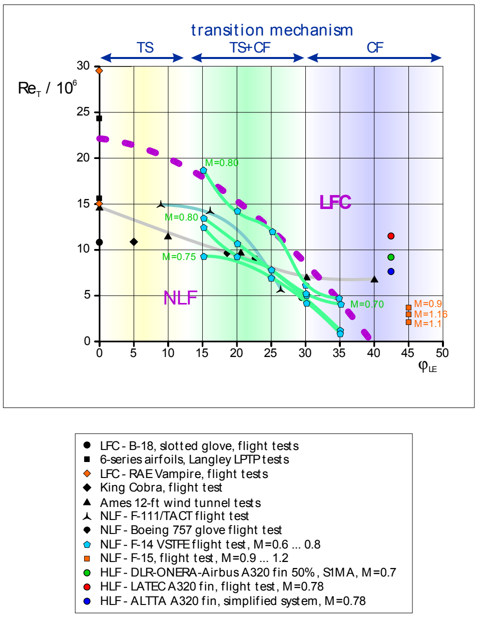


Figure 3. Applicability of Natural Laminar Flow (NLF) and Hybrid Laminar Flow Control (HLFC) for Reynolds number and wing sweep with respect to transition to Tollmien-Schlichtung (TS) and Cross-Flow (CF) instability mechanisms; experimental data included [23].

2.2. Active Load Alleviation

In general, aircraft is designed for extreme maneuver and gust load cases, which leads to heavy structure mass. Through maneuver and gust load alleviation technologies, the structure mass can be significantly decreased. For example, the NASA Sugar Volt design assumes that a properly designed active load alleviation system can reduce the wing weight by 25% [24].

The latest aircraft models produced by industry already incorporate several load alleviation technologies. Within the Airbus family these range from static application of differential flap settings to increase the maximum takeoff mass over relatively slow maneuver load alleviation functions covering symmetrical as well as asymmetrical maneuvers (e.g., A350) up to systems for the dynamic control of elastic modes and flutter (e.g., A320neo).

Today, it is not clear how large the potential of fully exploiting dynamic load alleviation techniques really is. Research in the past was often limited by computational and modeling capabilities, and by restrictions due to the then available sensor and actuator technology. Today, with the availability of advanced simulation tools and the introduction of more flexible electric actuation systems, more capable control systems and design for deformation using composite materials it should be possible to obtain larger benefits than in the past. Therefore, it is of interest to assess the potential of aggressive load alleviation techniques and then to design and optimize aircraft for rigorous application of this technique. The reduction of the loads via application of all available aerodynamic control devices coupled with the tailoring of the elastic properties of the flexible wing and the consideration of the control system early in the design phase could lead to a considerable reduction of the wing mass. We assume that by taking load control fully into account already in the early stages of aircraft design, the potential of this technology could be exploited much better than in current designs.

Preliminary studies [24–28] have shown that the application of flap systems for static gust and low dynamics maneuver load control has a potential to reduce takeoff mass and fuel consumption of long range transport aircraft. More aggressive load alleviation techniques and a wing planform designed to exploit these functions, as well as adapted thickness respectively, stiffness distributions are expected to increase the benefits to about a 25% reduction of the mass of the wing box, which can result in a 7% reduction of the fuel consumption [29].

The limit case would be a wing, designed as a dynamic spanload, minimizing the bending moment all over the wing span in all maneuver and gust cases dramatically. For example, in a symmetric 2.5 g load case, all additional loads due to the inertia of the fuselage and payload would be shifted towards the symmetry plane by deploying wing and possibly fuselage flaps. Also a wider fuselage cross section could help to shift the load more inboard. The inertia loads due to wing, engines and fuel mass would be compensated by adaptation of the lift distribution in the outer wing.

2.3. Technology for New Structure and Materails

One important way to enhance the aircraft fuel efficiency is to reduce the structure weight through introducing new metals and new composites with better material/structural properties [3]. In addition, new structure design and manufacturing concepts can also lead to aircraft structure weight savings. Researchers from NASA have carried out a comprehensive overview of the prevalent structure technologies potentially available for improving aircraft fuel efficiency [3]. As highlighted by the review, stitched composites are seen to be one promising solution for low-cost and lightweight structures, which can give around 10% weight reduction relative to a baseline with advanced composite sandwich structure [3]. Electronic Beam Free Form Fabrication (EBF^3) manufacturing is considered as a breakthrough for saving structure weight associated with significant cost and lead-time reductions [3].

Besides, Structural Health Monitoring (SHM) has also been identified as a promising technology for weight reduction by IATA Technology Roadmap [2] and NASA [30].

Except for the state-of-the-art material and structure developments, one very important task for structure research is to support other game-changing technologies, such as LFC and active load alleviation. For example, LFC requires porous structure, where multiple-shell structure can provide suitable differential pressure through suction plenum that is formed by tailoring.

A challenging aspect comes when the structure on the one hand has to fulfill additional requirements for future unconventional applications, but also for reducing the operation empty weigh itself. As such, radical new paradigms for structure studies are necessary.

Within the EWL project, a total structure weight reduction by 20% relative to today's technology has been preliminarily estimated.

2.4. Boundary Layer Ingestion

The main motivation of boundary layer ingestion is to make use of the boundary layer flow for improving the engine propulsive efficiency [31], i.e., "propulsor ingests and reaccelerates airframe boundary layer" [32]. Figure 4 shows a comparative study of the boundary layer ingestion (BLI) effect on propulsive efficiency.

According to the system study by NASA researchers [31], 3–5% fuel burn benefit can be achieved by BLI technology relative to a clean-inflow, pylon-mounted, advanced Ultra-High Bypass Ratio baseline turbofan engines. More aggressive fuel burn benefits can be expected from BLI, if larger percentage of boundary layer can be ingested [33,34]. Table 2 summarizes the recent research findings on BLI benefits for commercial aircraft.

Table 2. A summary of studies on aircraft level benefits of BLI.

Year and Authors	Methods	Aircraft Configuration	Benefits
2003, 2006 Kawai et al. [36,37]	System study	BWB	5.5–10% fuel savings
2007 Plas et al. [35]	System study	BWB (SAX40)	3–4% fuel savings relative to conventional engine configuration
2009 Hardin et al. [31]	System study	BWB	3–5% fuel burn benefit
2014 MIT [33,34]	Both experiments and numerical simulations	Double-bubble (D8)	6% experiment 9% numerical power savings
2017 Hall et al. [38]	Simulation	Double-bubble (D8)	9% mechanical power reduction with 40% of the fuselage boundary layer ingested
2017 Uranga et al. [39]	Experiment	Double-bubble (D8)	8.6% reduction of mechanical flow power requirement

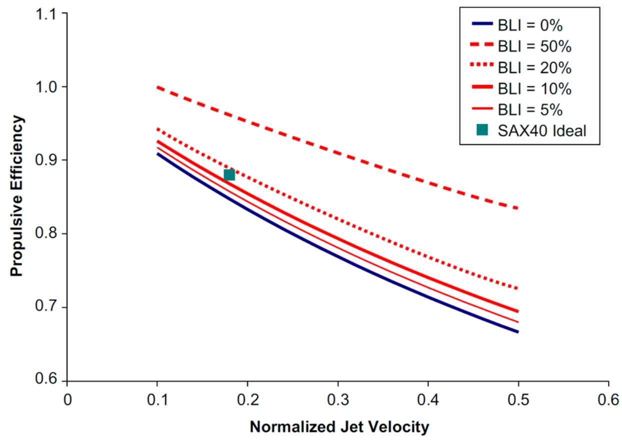


Figure 4. Propulsive efficiency with boundary layer ingestion (BLI) [35].

3. Aircraft Design and Optimization Methodologies

3.1. General Approach

To study the impacts of the abovementioned game-changing technologies, and to further explore the potential gains at overall aircraft level, an aircraft conceptual design and technology assessment platform is being developed within the EWL project. Similar to the recent work endeavored at Stanford University [40] and MIT [30], the flexible physic-based aircraft design and technology integration tool being developed in the frame of the EWL project has the advantage of handling technology assessment problems with a wide design space, which is extremely important for early-stage aircraft configuration and technology identifications. In addition, the design tool is built to be able to incorporate multidisciplinary results for building surrogates, which can give reasonably accurate predictions at the overall aircraft level. Following a typical aircraft conceptual/preliminary design logic [30,40–42]—especially the very comprehensive aircraft design platforms developed at the TU Braunschweig (PRADO tool [43]) and at the RWTH Aachen University (MICADO tool [42]) in Germany, some features and modelling strategies are illustrated as follows. It has to be noted that the tool developed within the EWL project has a very good compromise between complexity and fidelity levels, which is more suitable for aircraft technology assessment for such a joint research project as compared to other tools already being developed. Figure 5 shows general approach of the modelling strategies. The typical aircraft sizing process is shown on the right side and on the left side the multidisciplinary design optimization (MDO) process is shown. It has to be noted that all the design constraints have been already incorporated into the sizing process, i.e., no additional constraints are listed for the left part. In the following sections, different disciplinary study methodologies are introduced.

3.2. Parameterization of Aircraft Geometries

For overall aircraft level benefit and tradeoff studies, an effective and efficient parameterization or a common description of aircraft parameters is of great importance, especially when considering the potential complexities of data exchange for aircraft level technology and performance assessment and multidisciplinary optimization. Besides, parameterization is also a necessity when we consider the further air transport level estimation of emissions, noise, direct operating costs, or life cycle costs, which are dependent on aircraft parameters and operation parameters. Currently, there are several prevailing ways used in industries and academia for aircraft parameterization [41,42], and most have the capability to work with the DLR CPACS data format [44,45]. In the present modelling, the parameterization method is also based on DLR CPACS format.

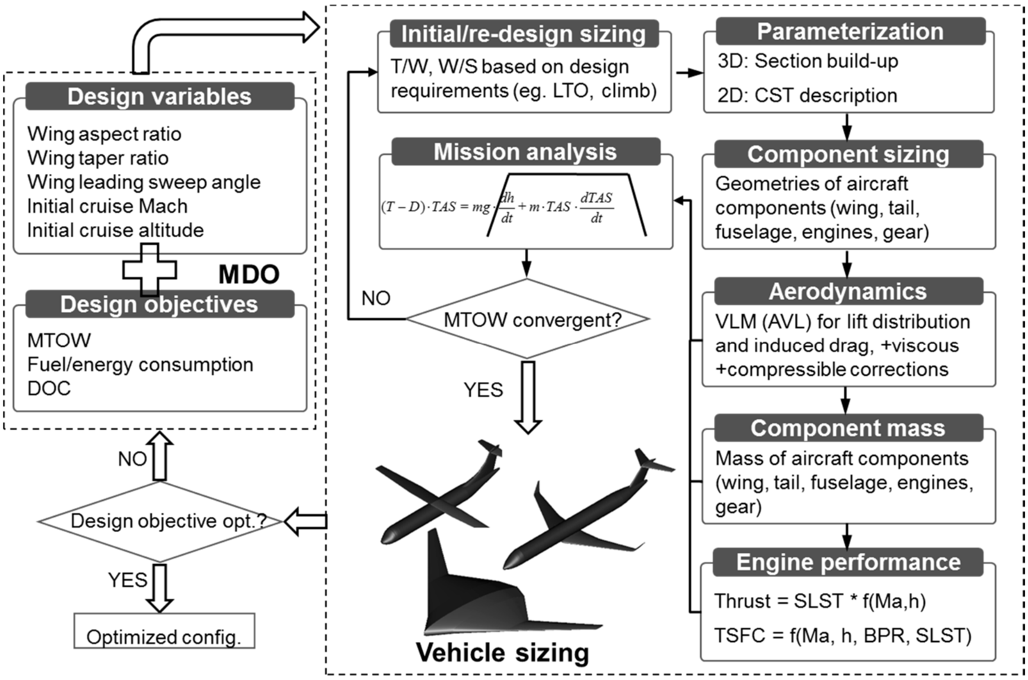


Figure 5. The flow diagram of the general approach for modelling aircraft level impacts.

3.3. Aerodynamic Modelling Approach

A component-based approach proposed by Gur et al. [46] is adapted to estimate the component aerodynamic performance for a given C_L, Ma, Re combination. The total drag coefficient C_D, total is categorized into three groups, i.e., the induced drag C_{Di}, the viscous drag $C_{D,vis}$ and the wave drag.

The induced drag is calculated using an advanced vortex lattice method, AVL, developed at the MIT by Prof. Drela [47].

The viscous drag is modelled as a function of equivalent skin-friction coefficient, form factor and the wetted area and reference area ratio. The equivalent skin-friction coefficient can reflect the laminar/turbulent flow impact. Equation 1 is used to capture the laminar flow control impact on the friction drag estimations, where C_F is the equivalent skin coefficient, $C_{F,laminar}$ represents the friction coefficient for full laminar flow condition and $C_{F,turbulent}$ represents the friction coefficient for the full turbulent flow condition, and LFC refers to the percentage of laminar flow, which is discussed in Section 2.2. The form factor is modelled to include the impact of geometry features such as thickness ratio, the quarter-chord sweep angle and flight Mach number Ma. The wetted area to reference ratio is an important indicator to reflect vehicle concepts. The exact of formulation of the viscous drag calculation as well as the definition of form factor and wetted area can be found in Ref. [46]. The wave drag is calculated based on the Lock's estimation method [48].

$$C_F = \mathrm{LFC} \times C_{F,laminar} + (1 - \mathrm{LFC}) \times C_{F,turbulent} \tag{1}$$

3.4. Structure and Component Masses

Generally, within the conceptual aircraft design stage, the component weight is determined based on statistical data or physics-based estimations, i.e., correlations based on historical aircraft or simplified models. It has to be noted that the most correlations are only valid for a certain range. For unconventional aircraft, such as BWB, necessary modifications are being made.

For blended wing body (BWB) configurations, one significant difference as compared to the conventional tube-and wing configuration is the pressurized cabin modelling. A sizing method proposed by NASA [49,50] is applied. In addition, the weight estimation of BWB cabin (center body) and aft center body cannot be directly derived from statistic regression due to the insufficiency of extant data. As such, a surrogate approach developed by Bradley [50] based on Finite Element Analysis is used in the modelling.

The following equation shows a generalized method for a statistics based wing mass calculation depending parameters:

$$W_{wing} = f(S_w, n_{max}, (t/c)_{avg}, \text{MTOW}, \ \text{MZF}, \ \lambda, \ \varphi_{1/4}) \tag{2}$$

where S_w is the wing area, n_{max} is the maximal design load, $(t/c)_{avg}$ is the average thickness to chord ratio, MTOW is the maximal takeoff weight, MZF is maximal zero fuel weight, λ is the wing taper ratio and $\phi_{1/4}$ is the chord line sweep angle. The aircraft wing mass can be calculated either using a simple regression and or a physics-based EMWET tool [51], which requires the following information as inputs.

1. Geometry data (leading edge coordinates, chord length, twist angle, incidence angle, airfoil data, etc.)
2. Mass data (MTOW, MZFW, MLW) including components attached to the wing
3. Operation data: flight level (FL), Mach number (Ma)
4. Structure (chordwise position of front and rear spars, rib pitch, etc.)
5. Materials information
6. Maximal load factor (1.0–2.5) to reflect the load alleviation technology

Other aircraft component masses are calculated using surrogates models, based on literature [40]. Additional structure progress factor is used to reflect the structure mass reduction by advanced materials and light weight design. It has to be noted that "structure progress factor" is currently a global reduction factor to scale the aircraft structure weight which has been delivered from in-house preliminary estimations.

3.5. Engine Performance

The engine performance calculations are based on published data, such as FAA/EASA engine certification data, ICAO engine emission database, etc. Howe [52] has formulated several empirical methods for engine available thrust at different flight speeds and flight altitudes, as well as the specific fuel consumption depending on speed and altitude. To give a more reliable prediction of the engine performance data, improvements have to be made. This is extremely important for new entry into service (EIS) engines as they usually incorporate new technologies that can significantly enhance the engine performance as compared to the historical data.

As a strategy, several parameters in Equations (3) and (4), which are taken from [52], can be corrected using more detailed and reliable data achieved from GasTurb [53] modelling.

$$T = T_{STS}[K_{1\tau} + K_{2\tau}BPR + (K_{3\tau} + K_{4\tau}BPR)Ma]\sigma^s \tag{3}$$

$$SFC = c\prime(1 - 0.15BPR^{0.65})[1 + 0.28(1 + 0.063BPR^2)Ma]\sigma^{0.08} \tag{4}$$

where T and SFC are available operating thrust and specific fuel consumption at desired given condition, T_{STS} is the sea level static thrust, BPR is the bypass ratio, σ is the air density ratio (operating flight altitude to sea level), which represents the impact of flight altitudes. K_{it}, s, and c' are to-be-determined factors.

3.6. Mission Study Approach

The total flight mission is discretized into sufficiently small mission segments that are analyzed by using Newton's laws of motion, where the aircraft can be considered as a mass point. The power equilibrium needs to be fulfilled, i.e., the net power of thrust and drag transforms to the potential and kinetic energy changes. Within the mission calculations, an iterative process is employed to reflect the changes of variables in each mission segment. The aerodynamic polar and engine performance parameters are interpolated for the full flight mission usage, which, as mentioned earlier, are dependent on flight Mach number and flight altitude.

The mission tool has employed the conditions for more realistic operation conditions. In particular, the lift-to-drag ratio L/D has been considered as a function of true airspeed (TAS), flight altitude (h) and the current aircraft mass (m) which is updated by the fuel consumption in previous mission segment. Similarly, the specific fuel consumption (SFC) varies with TAS, h and the engine thrust (T) that is determined by the current aerodynamic drag.

In each mission segment, the basic relationship is fulfilled: power of thrust and drag = rate of change of potential energy + rate of change of kinetic energy + secondary power off-takes. The whole mission iterates till the design range is reached. As operation conditions also play very important roles in the aircraft fuel consumptions. To avoid additional impacts from operational aspects, predefined flight profile that are typical for each aircraft types have been assumed for fuel burn calculations. The predefined flight profile satisfies flight constraints such as flight physics constraints and engine performance constraints.

4. Results

In this section, overall aircraft level results are presented for three different configurations. The reference aircraft configuration with year-2000 technologies are summarized first for further comparison studies, i.e., the EWL developed aircraft concepts and identified technologies for 2050 will be checked with the Flightpath 2050 goals. Then, an overall aircraft level verification study of the tools as well as sensitivity studies of new technologies are carried out. After that, the fuel efficiency results for optimal aircraft configurations with year-2050 best assumed technology scenarios will be presented and compared with data of baseline configurations.

4.1. Baseline Configurations

Within the EWL project, three aircraft configurations are defined to represent regional/short range, medium range and long range. Table 3 summarizes the main characteristics of the three configurations. It has to be noted that for the first stage of our studies, we carry out the aircraft concept studies by integrating new aircraft-associated technologies and aircraft optimization. As such, only conventional energy storage and conversion systems are considered. Through aircraft level technology integration and optimization, the on-board energy and power requirements can be significantly reduced, which enables the applications of new energy systems. In this paper, only the first part (aircraft level technology integration and optimization) will be covered.

Table 3. Main features of the three aircraft configurations defined within EWL project.

Aircraft Category	Regional/Short Range (SR)	Medium Range (MR)	Long Range (LR)
Seat capacity	100	150–200	300–400
Design range (km)	1000	4500	15,000
Concept	Tube and wing, potentially developed to pure electric propulsion	Tube and wing or blended wing body	Blended wing body

In general, a reasonable way to carry out comparison study for aircraft emission reductions is to compare the fuel consumption/CO_2 emission for the design mission (relative to a reference aircraft with the same/similar design payload and design range) [3]. It has to be noted that this way of comparison might have additional coupled effects from operational aspects, which could further influence the technology assessment and aircraft level comparing studies. To minimize the coupled impacts, we choose preferably the same (or at least as close as possible) flight range and seat capacities for comparison.

In this section, fuel efficiency (generally carbon emission can be seen proportional to fuel consumption) is used to show the overall aircraft level benefits through technology progress. As such, Table 4 lists the data for regional/short, medium, long range reference aircraft, which includes aircraft types, year of first flight, typical seat capacity, design range, and fuel efficiency for design range with typical payload.

Table 4. Representative data for regional/short, medium, long range reference aircraft (fuel efficiency data compiled based on manufacture brochures and literature [54]).

Items	Regional/Short Range			Medium Range		Long Range	
Representative types	ATR 72–500	Bombardier CRJ900	Embraer E-Jet-170	Airbus A320-200	Boeing 737–800	Airbus A330-200	Boeing 777–200ER
Year of first flight	1997	2001	2002	1993	1997	1997	1996
Seat capacity (typical)	68	86	66	150	174	295	301
Design range (km)	1452	2553	3982	5090	5575	11,000	11,000
Fuel efficiency at typical payload and design range (kg/seat/100 km)	2.03	2.29	3.04	1.93	1.80	2.33	2.69

For better representation, we have selected not only turboprop but also turbofan aircraft models for the studies of the regional/short range aircraft group. The medium range and long range flight groups, we have chosen one Airbus aircraft and one Boeing aircraft, respectively. The data in Table 4 are derived from official brochures of the corresponding manufactures. To be compatible with the Flightpath 2050 requirements, the best fuel-efficiency aircraft in each category are chosen, i.e., 2.03 kg/seat/100 km for regional/short range category, 1.80 kg/seat/100 km for medium range category and 2.33 kg/seat/100 km for long range category.

4.2. Verification

To verify the whole modelling tools and the correctness of the tool integrations, we use the Central Reference Aircraft data System (CeRAS: is a validated reliable reference design data of commercial aircraft, https://ceras.ilr.rwth-aachen.de/, accessed on 3 November 2017) aircraft for comparing studies. The CeRAS short/medium range reference aircraft (CSR-01) has a design range of 2750 NM, a typical seat capacity of 150, and a maximal take-off weight (MTOW) of 77,000 kg. A three-dimensional (3D) view of the reference aircraft is given in Figure 6. The comparison results such as take-off weight, operating weight empty (OWE) and fuel burn between EWL medium range aircraft (EWL-MR) and CSR-01 are listed in Table 5. As can be seen in the table, the results calculated using the tools developed within EWL project gives quite good predictions with a maximal deviation of 3%, which is acceptable for the preliminary technology assessment (For component level analysis, the error can be slightly larger due to the simplified methods utilized. Considering radically new technologies and aircraft concepts, a more sophisticated error study is planned to be carried out at the next stage of EWL project).

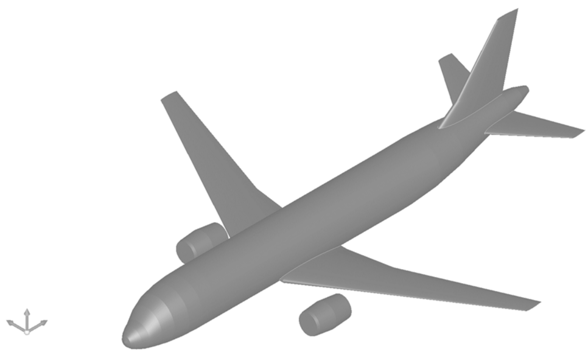


Figure 6. CSR-01 aircraft 3-D view.

Table 5. Comparison of the major aircraft design results between CSR-01 and EWL-MR.

Parameter	CSR-01	EWL-MR	Deviation (%)
Passenger number	150	150	-
Design range (NM)	2750	2750	-
Take-off weight (kg)	74,102	75,157	1.42
OWE (kg)	42,100	42,035	−0.15
Fuel burn (kg)	15,420	15,835	3.05

4.3. Sensitivity Study of Technology Progress

In this sub-section, sensitivity studies are carried out to show the impacts of different technologies addressed in Section 2. In addition, the overall aircraft level impacts of wing aspect ratio are also discussed.

Figures 7 and 8 show the sensitivity study results of aircraft fuel burn and MTOW impacts of the focused technology combinations. For the four focused game-changing technologies, both fuel burn and MTOW impact studies have six combinations. To better visualize the data, the left bottom points for all the subplots show the baseline technologies, i.e., fuel burn or MTOW changes are zero. Likewise, the top right points for all the subplots represent the best assumed technology scenarios. As shown in Figure 7, the combination of LFC and load alleviation can bring the most fuel burn savings while the combination of structure improvement and BLI technology has the least. It can be found in Figure 8 that the combination of LFC and structure improvement bring the most MTOW benefit while load alleviation and BLI have slightly lower MTOW benefit. In general, from the results in Figures 7 and 8 show one can observe that the technology improvements in our study have large impact on the overall aircraft performance.

To show the achievable fuel burn and MTOW benefits of best assumed technology scenarios, an integration of high fidelity methods or corrections from high fidelity results is necessary. For this paper, the results of high fidelity computational fluid dynamics (CFD) analysis for LFC [55] have been used as reduction factors to update the aerodynamic analysis introduced in Section 3. The CFD calculated friction drag reduction for the wing and tail planes are around 68%, for the fuselage is 72%, which corresponds to a LFC factor of 0.72, i.e., the marked points in Figures 7 and 8 referring to "Max. EWL LFC benefit". It has to be noted that the detailed coupling effect of different technologies has not been taken into account within this manuscript, which will be the focus of the second stage of the EWL-project. Though, preliminary studies within the first stage of EWL project have shown good feasibility of each individual technology goals.

As one of the most important wing planform parameters, wing aspect ratio has very significant impacts on the overall aircraft performance, such as weights, fuel burn, and costs. Figure 9 represents the aspect rations impacts on MTOW, OWE, fuel burn, wing mass, and direct operating cost (DOC), for baseline technology scenario (cf., Figure 9a), only LFC technology integrated (cf., Figure 9b) and 2050 best assumed technology scenario (cf., Figure 9c). It has to be noted that due to the much stronger changes in wing mass, the wing mass relative change to baseline is shown according to the right y-axis scale and the relative change to baseline for the rest of the parameters are plotted based on the left y-axis scale. As can be seen in the figure, the overall trend of the aircraft parameters shows good sensitivity, e.g., the wing mass increases with an increased aspect ratio, and fuel burn decreases with increased aspect ratio for a certain range of aspect values. For current technology, the DOC minimum gives an optimal aspect ratio around 11.5, which is slightly larger than the reference medium range aircraft A320-200 that has an aspect ratio of 9.5. For the case of only integrating LFC technology, the curves are slightly different and gives an optimal aspect ratio around 14 for DOC minimum. With all game changing technologies integrated, the aspect ratio is even larger (around 18) for minimal DOC.

Figure 10 shows the aerodynamic polar of the reference configuration and DOC-optimized configuration with LFC technology integrated for the medium range aircraft. It has to be noted that for better comparison, the flight conditions are set to be identical, i.e., Mach number of 0.78 and flight altitude of 11,000 m for both cases. As can be seen in the figure, the lift-to-drag ratio (L/D) has almost been doubled for the LFC technology. Besides, the plateau of lift coefficient for best L/D shifts from 0.6 for baseline technology to 0.4 for LFC integration, which indicates that an aircraft level optimization accounting for operational conditions (flight altitude and speed) is necessary to maximize the aircraft benefits of integrating new technologies.

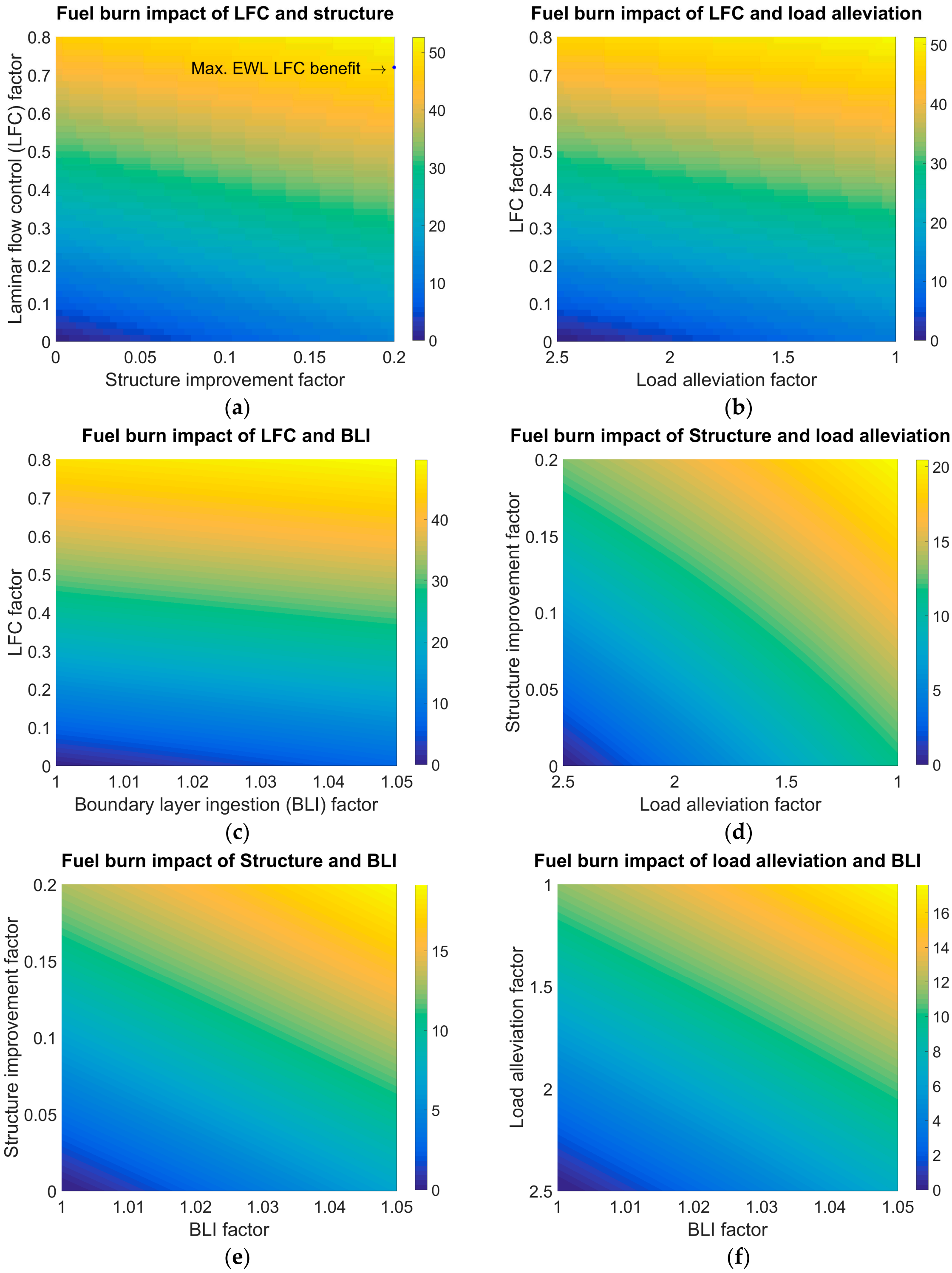


Figure 7. Sensitivity study on fuel burn impact of four focused technologies (Note that the fuel burn impact is illustrated using percentage of reduction, in which positive values refer to fuel burn reduces relative to baseline).

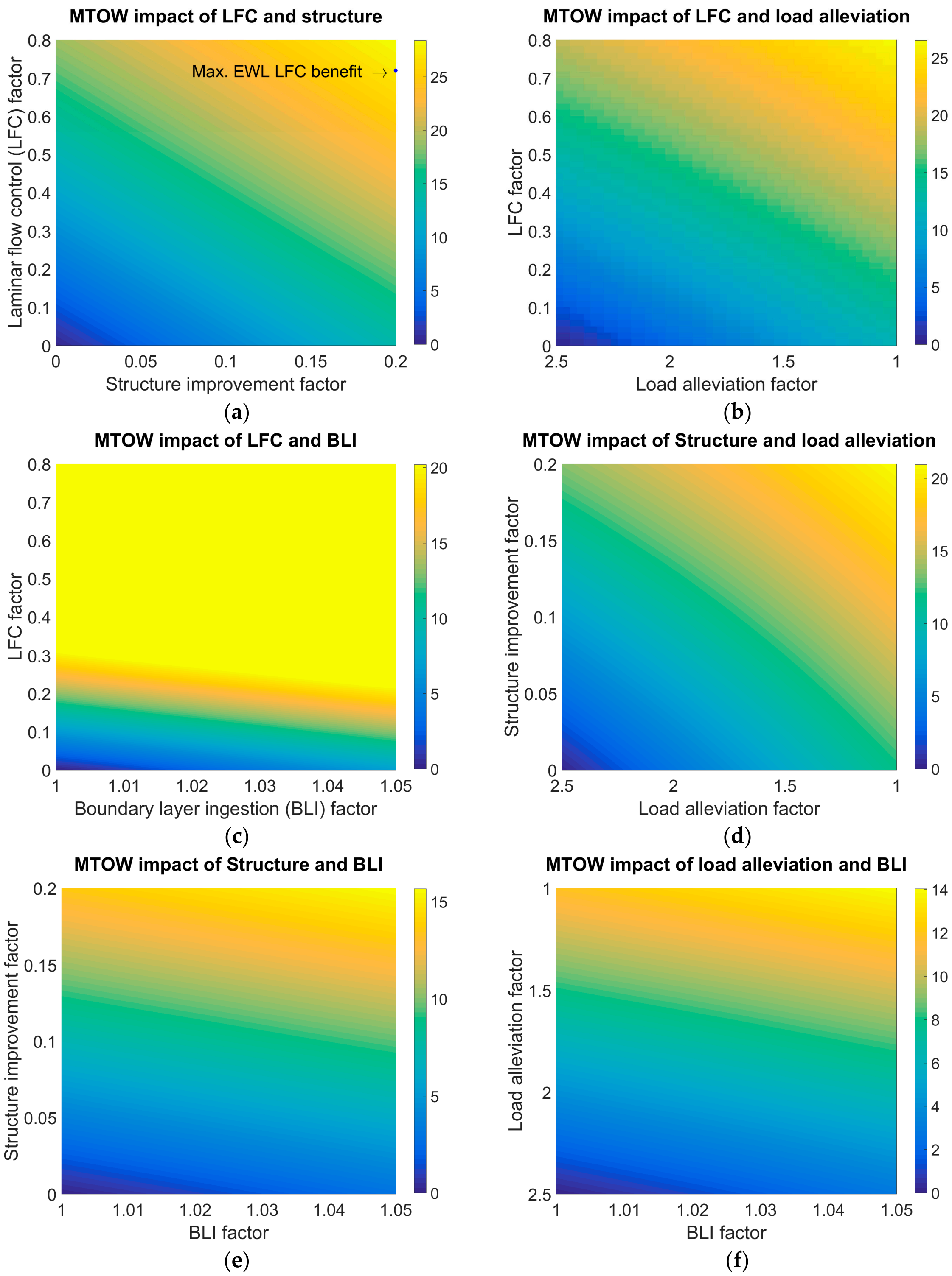


Figure 8. Sensitivity study on maximal take-off weight (MTOW) impact of four focused technologies (Note that the MTOW impact is illustrated using percentage of reduction, in which positive values refer to MTOW reduces relative to baseline).

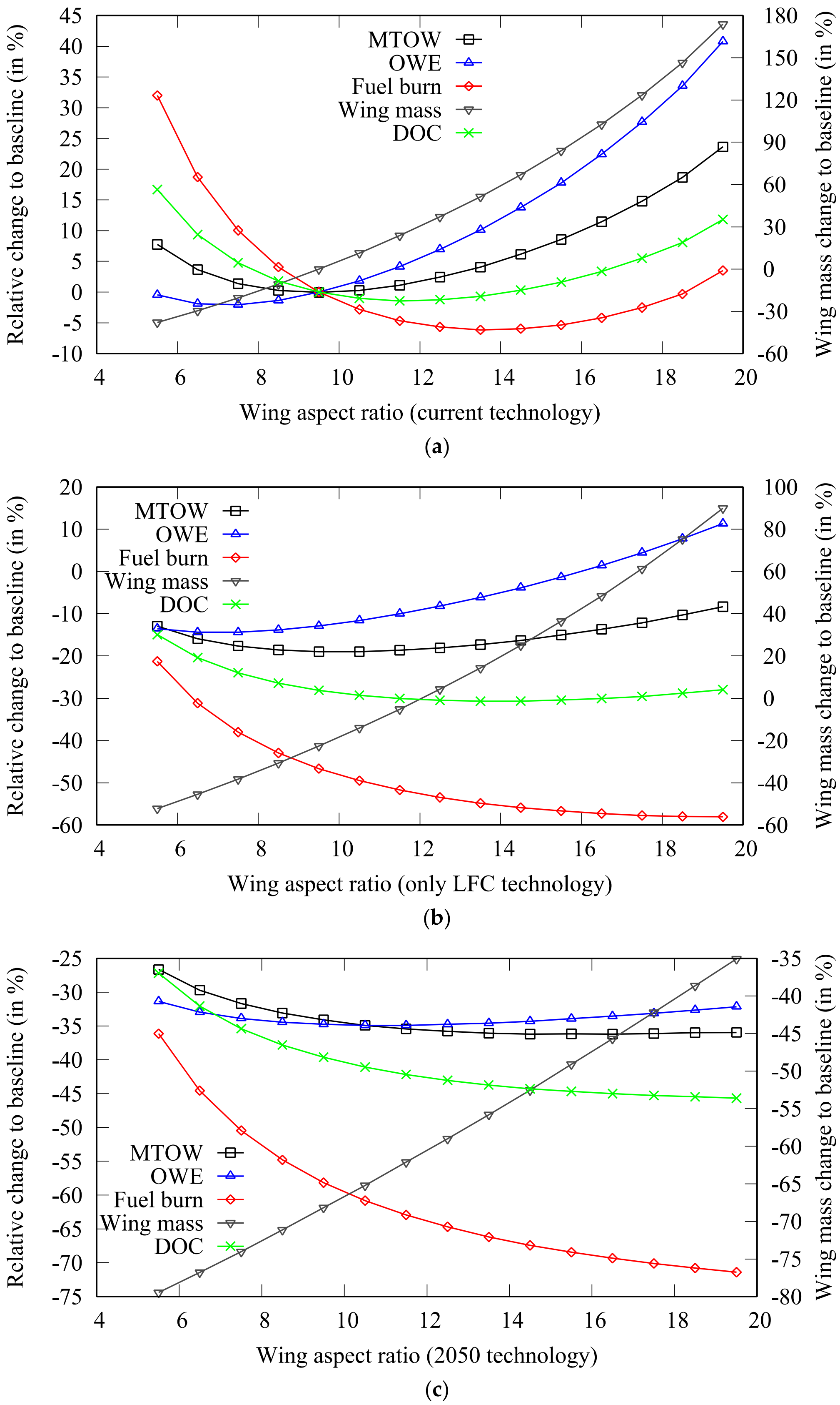


Figure 9. Sensitivity study of wing aspect ratio impacts of medium range aircraft. (**a**) Current technology; (**b**) Only LFC technology integrated; (**c**) Best assumed technology scenarios for 2050.

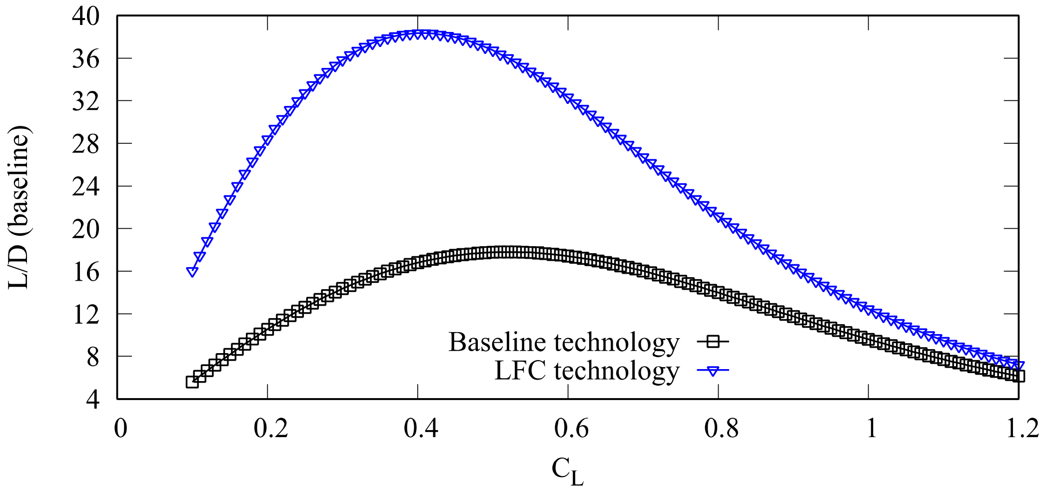


Figure 10. Aerodynamic polar for medium range aircraft.

4.4. Overall Aircraft Level Benefits

In this sub-section, the overall aircraft benefits through integrating game-changing technologies as well as aircraft level multi-disciplinary optimization will be presented and compared with the baseline configuration results.

Figure 11 shows the overall aircraft benefits for the combination of all four technologies for EWL-MR relative to the baseline technologies. As can be seen in the figure, for single technology improvement, LFC brings the most fuel efficiency improvement (46.7%) and BLI contributes 7.3% improvement in fuel efficiency. In total, the cumulative fuel efficiency can be enhanced by 58.1%. The results are reasonably comparable to the results of the NASA ERA project [54], which has a fuel burn reduction of around 40%. The more aggressive fuel burn reduction of EWL project is due to the very significant LFC impacts.

Figure 12 shows the comparison of the EWL reference aircraft and the new designed aircraft with the best assumed technology scenarios based on preliminary results from the first stage studies for the EWL project. An ATR 72-500 like aircraft is chosen as the baseline for regional/short range aircraft; an A320 like aircraft is selected as the baseline for medium range aircraft. For long range aircraft, an A330 like aircraft is chosen for reference, as there are no real blended wing body concepts for commercial airliners. As can be found in the figure, the wing area has been reduced and the aspect ratio has been increased. Note that for laminar flow control constraints, the leading edge sweeps are relatively low.

Table 6 summarizes the major aircraft parameters for resulting design solutions at the first stage of our project. It has to be noted that for the long range BWB concept, the wing area, aspect and leading edge sweep all refer to the outer wing.

Table 7 summarizes the fuel efficiency through introducing new technologies and carrying out aircraft optimization. As can be seen in the table, the fuel efficiency can be improved significantly for the optimized configurations with best assumed technology scenarios as compared to the year-2000 best fuel-efficiency aircraft baselines. For the long range BWB concept, 75.1% fuel efficiency improvement/carbon emission reduction already reaches the Flightpath 2050 goal, i.e., 75% CO_2 emission reduction relative to year-2000 baseline. However, the medium range with a 65.5% fuel efficiency enhancement can still not reach the Flightpath 2050 goal. The fuel efficiency progress of regional/short range group aircraft by 40.8% is far under the goal. Therefore, to realize the challenging CO_2 reduction goal of Flightpath 2050, new energy storage and conversion system that can generate less or zero on-board carbon emissions are necessary.

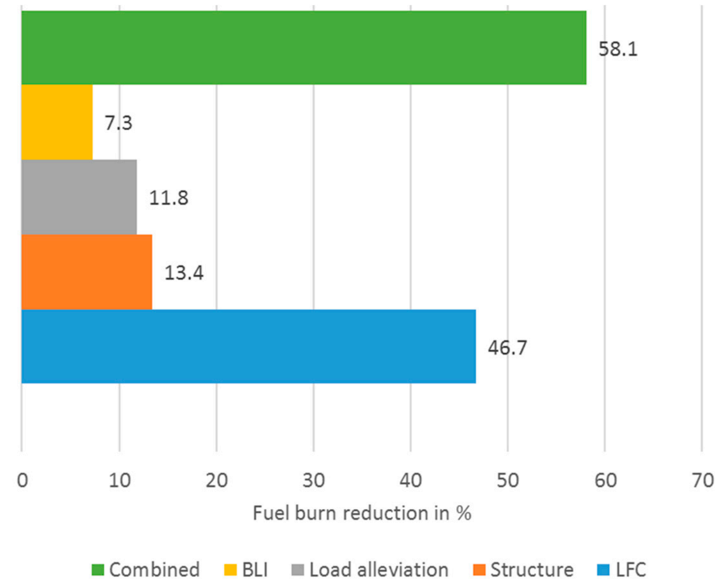
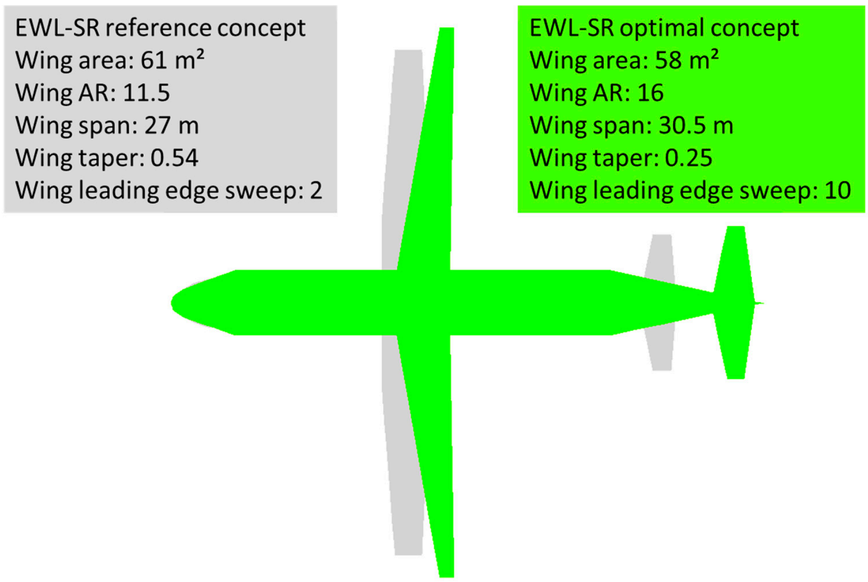
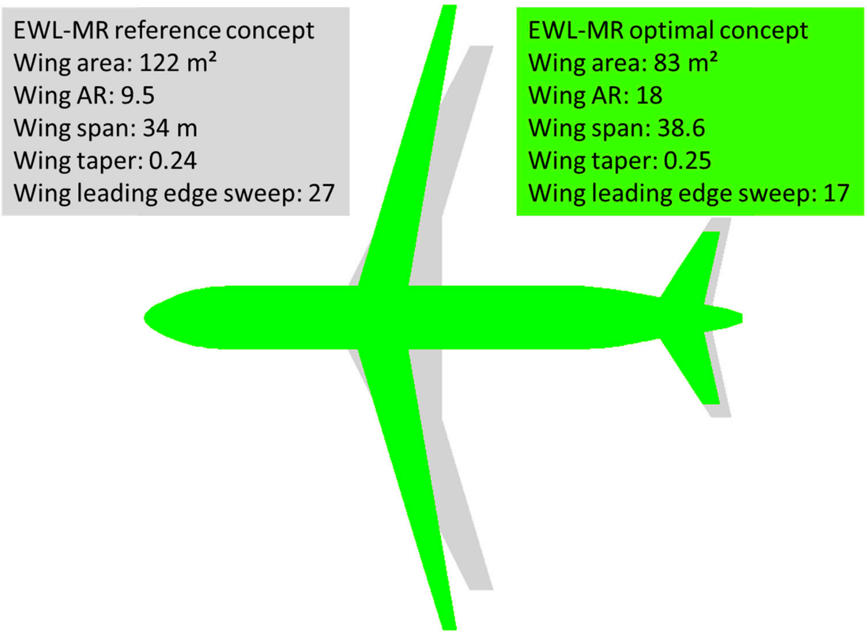


Figure 11. Summary the fuel burn impact of four technologies for EWL medium range aircraft EWL-MR.

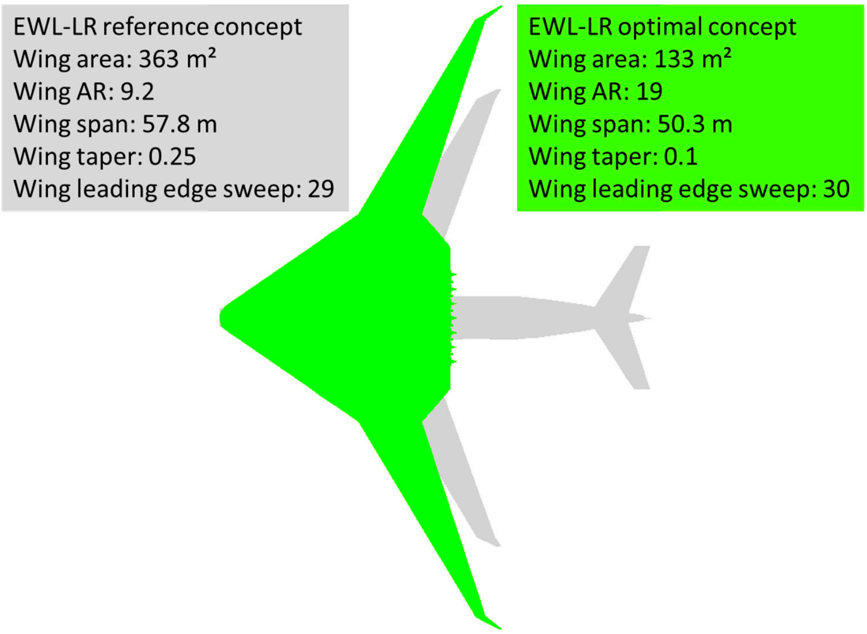


(**a**)

Figure 12. *Cont.*



(**b**)



(**c**)

Figure 12. Comparison of EWL reference aircraft and new designed aircraft with best assumed technology scenarios based on preliminary results from the first stage studies of the project (Note that to better visualize the aircraft concept, three different scales have been chosen for sub-plot **a**, **b** and **c**). (**a**) Short range aircraft; (**b**) Medium range aircraft; (**c**) Long range aircraft.

Table 6. Summary of the overall aircraft parameters.

Aircraft Category	Regional/Short	Medium Range	Long Range
MTOW (t)	25	48	132
OWE (t)	13	28	78
Wing area (m^2)	58	83	133
Aspect ratio (-)	16	18	19
Leading edge sweep (°)	10	17	30

Table 7. Summary overall aircraft level benefits through new technologies and optimization.

Aircraft Category	Year-2000 Best Fuel Efficiency (kg/seat/100 km)	EWL-2050 Best Fuel Efficiency (kg/seat/100 km)	Potential Fuel Efficiency Improvement (%)
Regional/short	2.03	1.20	40.8
Medium range	1.80	0.62	65.5
Long range	2.33	0.55	75.1

5. Discussion

In the previous sections we have studied the potential benefits through integrating new aircraft-associated technologies. Another significant contribution to improving the aircraft fuel efficiency comes from engines. As predicted by Rolls-Royce, engine related technologies can make around 30% contribution toward ACARE Flightpath 2050 Targets [56].

In addition to the technology parts, other operational aspects, such as multiple-stop-operation, air-refueling, aircraft formation flight, cruise step climbs, etc. [57] should also be taken into account for exploring the benefits. As such, these aspects should also be taken into account for aircraft design work to make the overall trade-offs and design for optimal operations.

As already mentioned previously, the current work only covers the aircraft-associated technology integration and optimization at a conceptual/preliminary design fidelity level. The detailed high-fidelity data will be provided from the team-members of the project, which will be integrated in the whole aircraft level studies. In addition to the conventional energy systems, detailed new storage and conversion systems also need to be modelled within the framework.

1. System energy conversion efficiency (e.g., battery to propulsive power)
2. Energy density of energy storage systems
3. Power density of energy conversion systems
4. Tank systems (mass and volume)

Figure 13 shows the data flow interacting with different disciplinary studies. It has to be noted that different disciplinary studies have quite often different fidelity levels. As such, in some cases it is time-consuming or even impractical to integrate the sub-system modelling into the overall approach. The possible solution is to build-up surrogates on condition that an inline sub-system calculation is considered to be unnecessary.

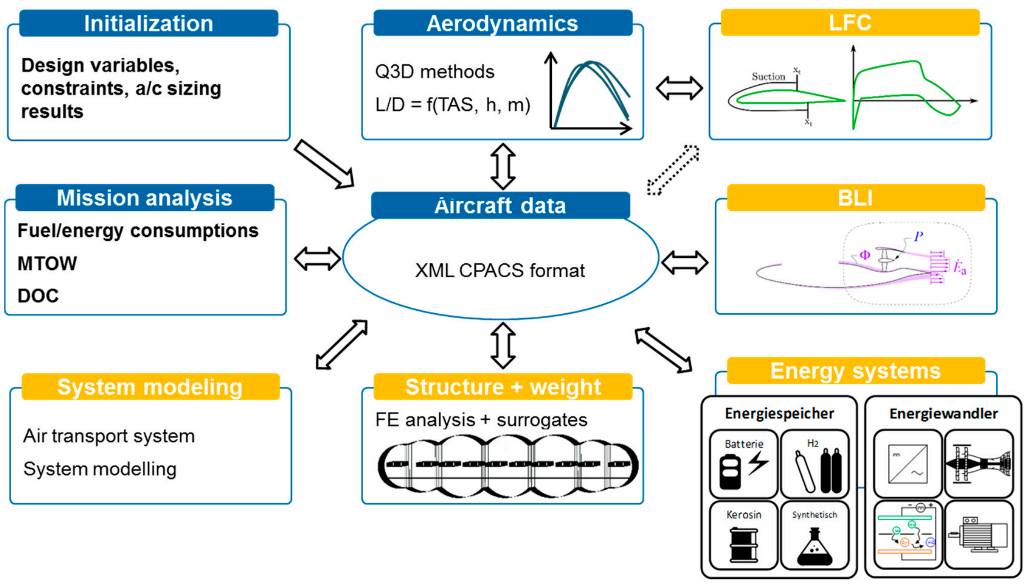


Figure 13. Representation of data flow interacting with different disciplinary studies.

6. Conclusions

In the context of Energy System Transformation in Aviation research project, a generalized framework is developed to investigate the airframe technologies and new energy systems. A verification study with comparison to a reliable CSR-01 reference aircraft showed very good agreement. The study on the technology progress level impacts for both MTOW and fuel burn showed good sensitivity.

With a combination of four major EWL-identified technologies, the total fuel burn at the design range is reduced by 58% for medium range aircraft without carrying out aircraft optimization.

By optimizing aircraft with best assumed technology scenarios, fuel efficiency can be substantially improved for all three aircraft categories. To be specific, the BWB concept for long range aircraft have shown the most promising fuel efficiency improvement or carbon emission reduction, which can realize the Flightpath 2050 goal. While the other two tube and wing concepts are not able to reach the emission reduction goals, which indicates that further applications of new energy systems are necessary.

For future work, the coupled effect of game-changing airframe technologies and radical new energy systems have to be investigated (reduced energy requirement relaxed the application of new energy systems). Besides, full aircraft level MDO with more design variables, both from aircraft-associated parameters but also from engine and operational parameters, have to be carried out for further exploring the benefits of energy system transformations in aviation.

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Author Contributions: Y.L. designed and implemented the simulation tools, carried out the simulations, analyzed the results, and wrote the main part of the paper. M.H. involved in the writing of the technology overview section, especially the laminar flow control and active load alleviation parts. A.E. and P.H. involved in refining the storyline, and also elaborated the introduction section and the discussion section.

Conflicts of Interest: The authors declare no conflict of interest.

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